GE Global Research

Exergy Based Microturbine Analysis

Karl Sheldon
AIMS Core Designer

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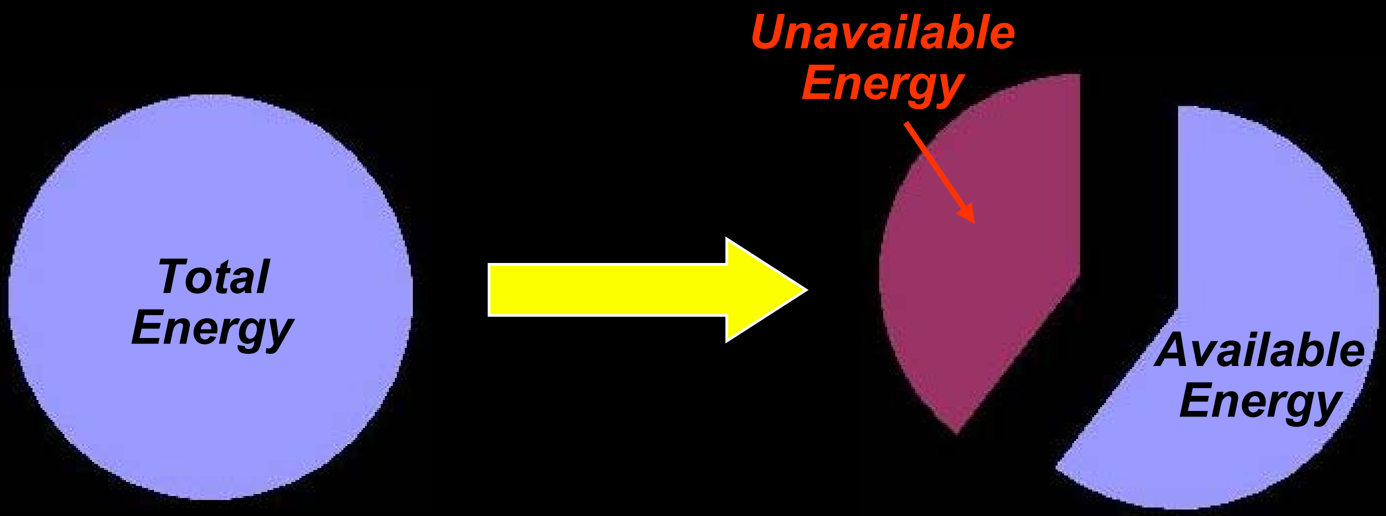
Outline

- What is Exergy ?
- First Law Versus Second Law
- Second Law Application – Air Standard Brayton Cycle
- Chemical Availability And Combustion Losses
- Summary

What is Exergy ?

- *Exergy Represents the Maximum Work Potential A Device Can Deliver*
- Term Made Popular in Europe in 1950’s
- Synonymous with “Availability” (Term introduced by M.I.T. in 1940’s)
- Unlike Energy, Exergy Can Be Destroyed
  - ✓ Friction
  - ✓ Uncontrolled Expansion/Compression
  - ✓ Heat Transfer
- Allows For Greater Understanding of Component and System Efficiencies



First Law of Thermodynamics

$M_{air\_earth} = 1.03 \times 10^{19}$ lbm

$T_0 = 59\ °F$

$E_{air\_earth} = 1.278 \times 10^{21}$ BTU

$t = 1.0 \times 10^{6}$ years

$\eta = 0.01$

$$P_{air\_earth} = (E_{air\_earth} \times \eta) / t$$

$$P_{air\_earth} = 427.4 \text{ MW}$$

The First Law of Thermodynamics deals with the *quantity* of energy and asserts that energy cannot be created or destroyed

Second Law of Thermodynamics

$M_{air\_earth} = 1.03\text{x}10^{19}$ lbm

$T_0 = 59$ °F

$E_{air\_earth} = 1.278\text{x}10^{21}$ BTU

$t = 1.0\text{x}10^{6}$ years

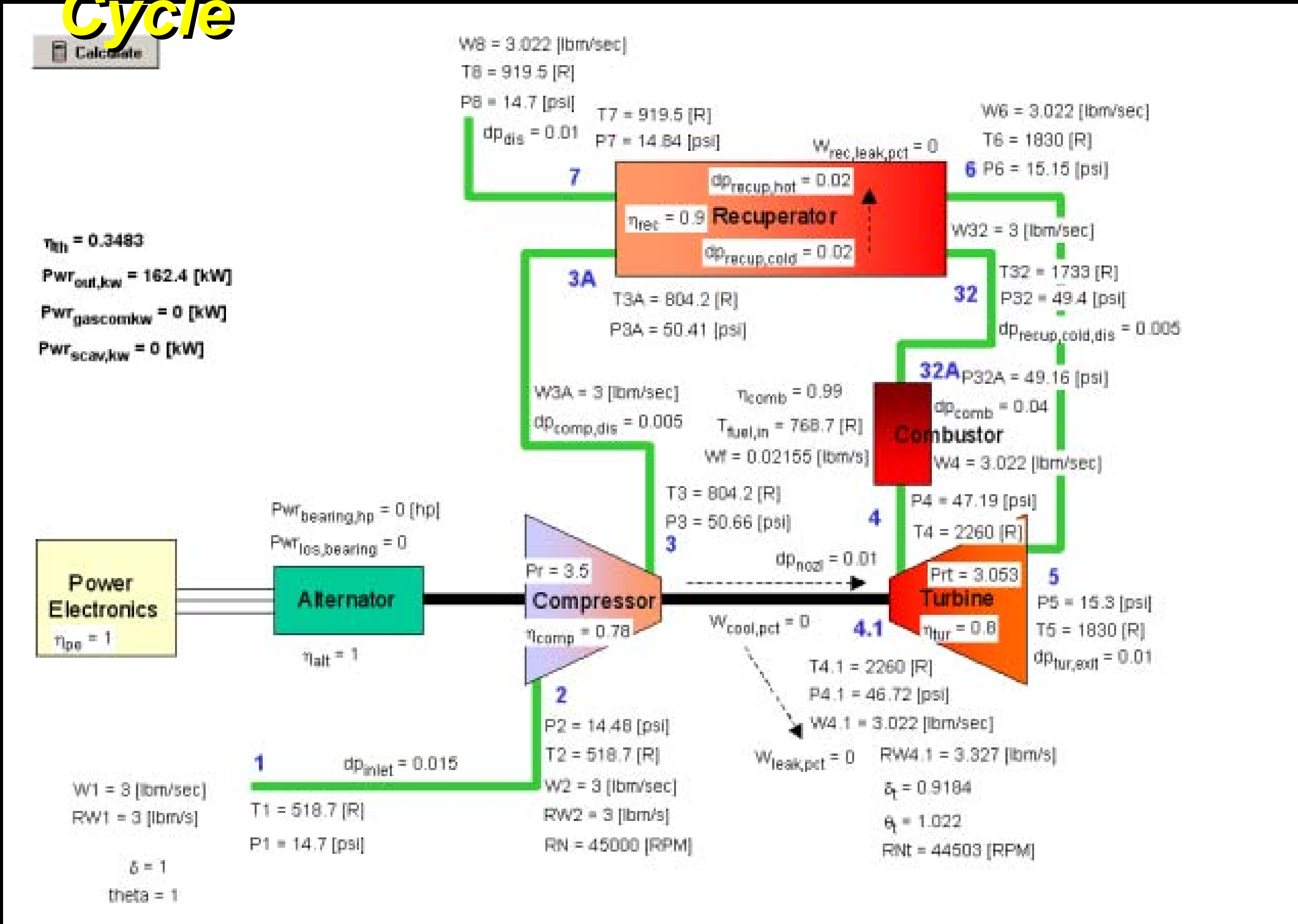
$\eta = 0.01$

$W_{air\_earth} = (1\text{-}T_{sink}/T_{source}) \text{ x } Q_{in}$

$W_{air\_earth} = 0$

The Second Law of Thermodynamics deals with the *quality* of energy and the degradation of energy during a process

Recuperated Air Standard Brayton Cycle



First And Second Law Work Together

$$q_{avail\_out} = (h_8 - h_1) - (s_8 - s_1)\cdot T_o$$

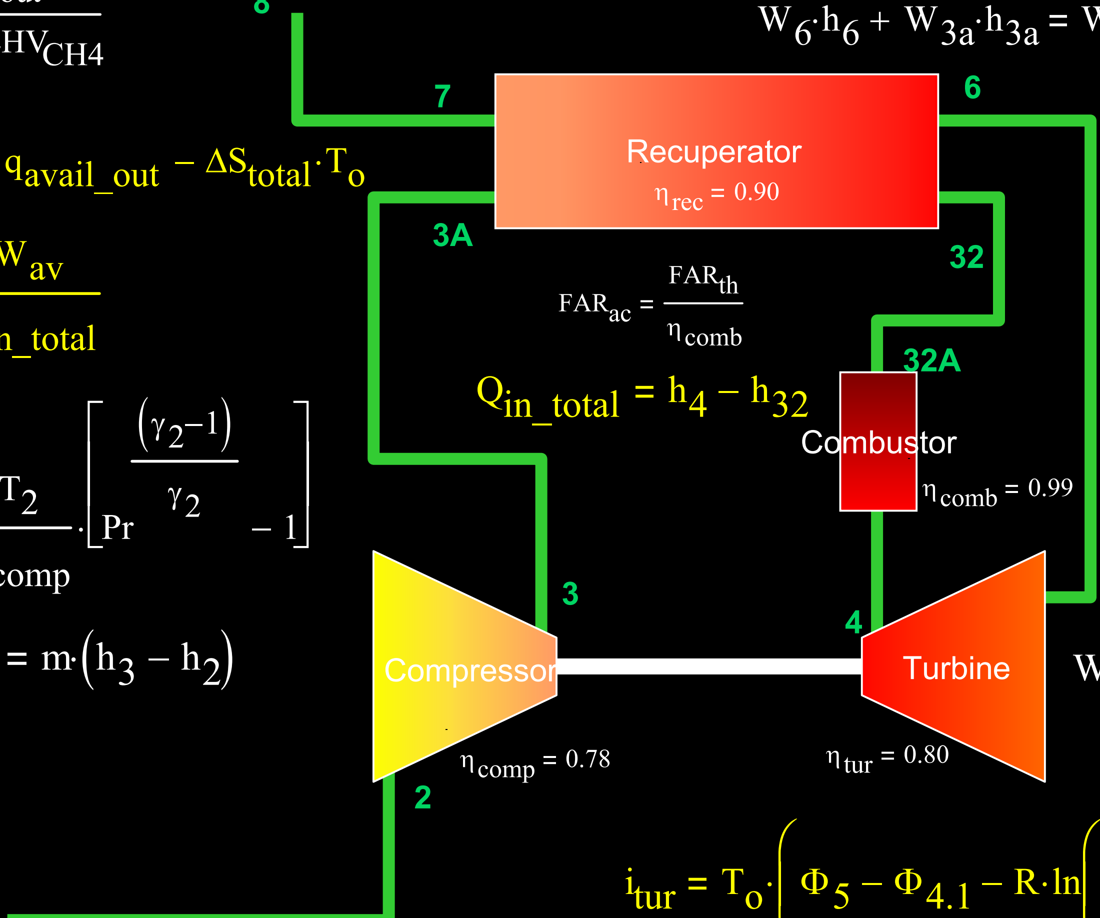
$$\eta_{rec} = \frac{h_{32} - h_{3a}}{h_6 - h_{3a}}$$

$$\eta_{th} = \frac{P_{out}}{W_f \cdot LHV_{CH4}}$$

$$W_6 \cdot h_6 + W_{3a} \cdot h_{3a} = W_{32} \cdot h_{32} + W_7 \cdot h_7 + Q$$

$$W_{av} = Q_{in\_total} - q_{avail\_out} - \Delta S_{total} \cdot T_o$$

$$\eta_s = \frac{W_{av}}{Q_{in\_total}}$$



$$FAR_{ac} = \frac{FAR_{th}}{\eta_{comb}}$$

$$Q_{in\_total} = h_4 - h_{32}$$

$$\Delta S_{total} = \sum \Delta s_i$$

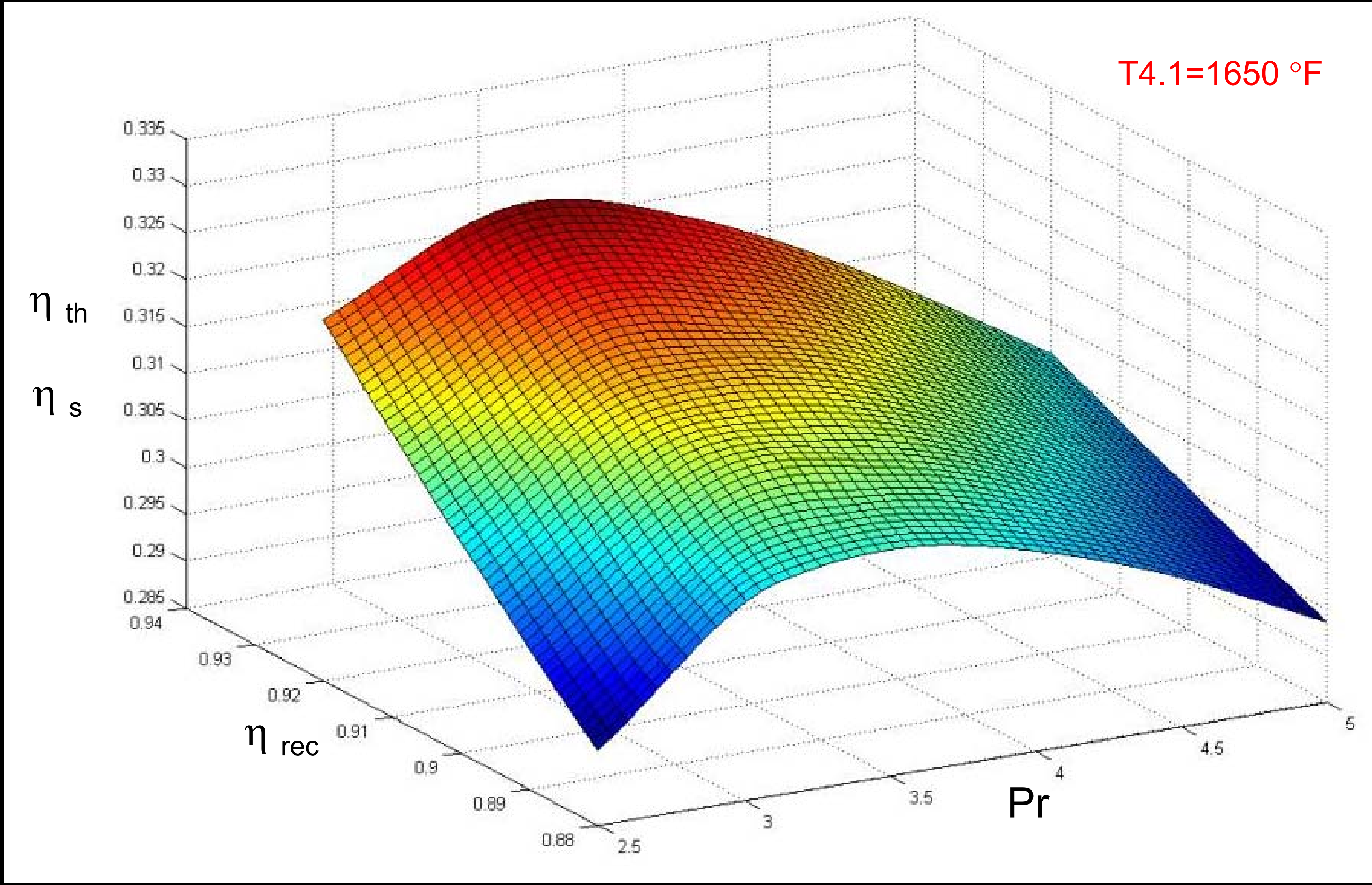
$$T_3 - T_2 = \frac{T_2}{\eta_{comp}} \cdot \left[Pr^{\frac{(\gamma_2 - 1)}{\gamma_2}} - 1 \right]$$

$$W_{comp} = m \cdot (h_3 - h_2)$$

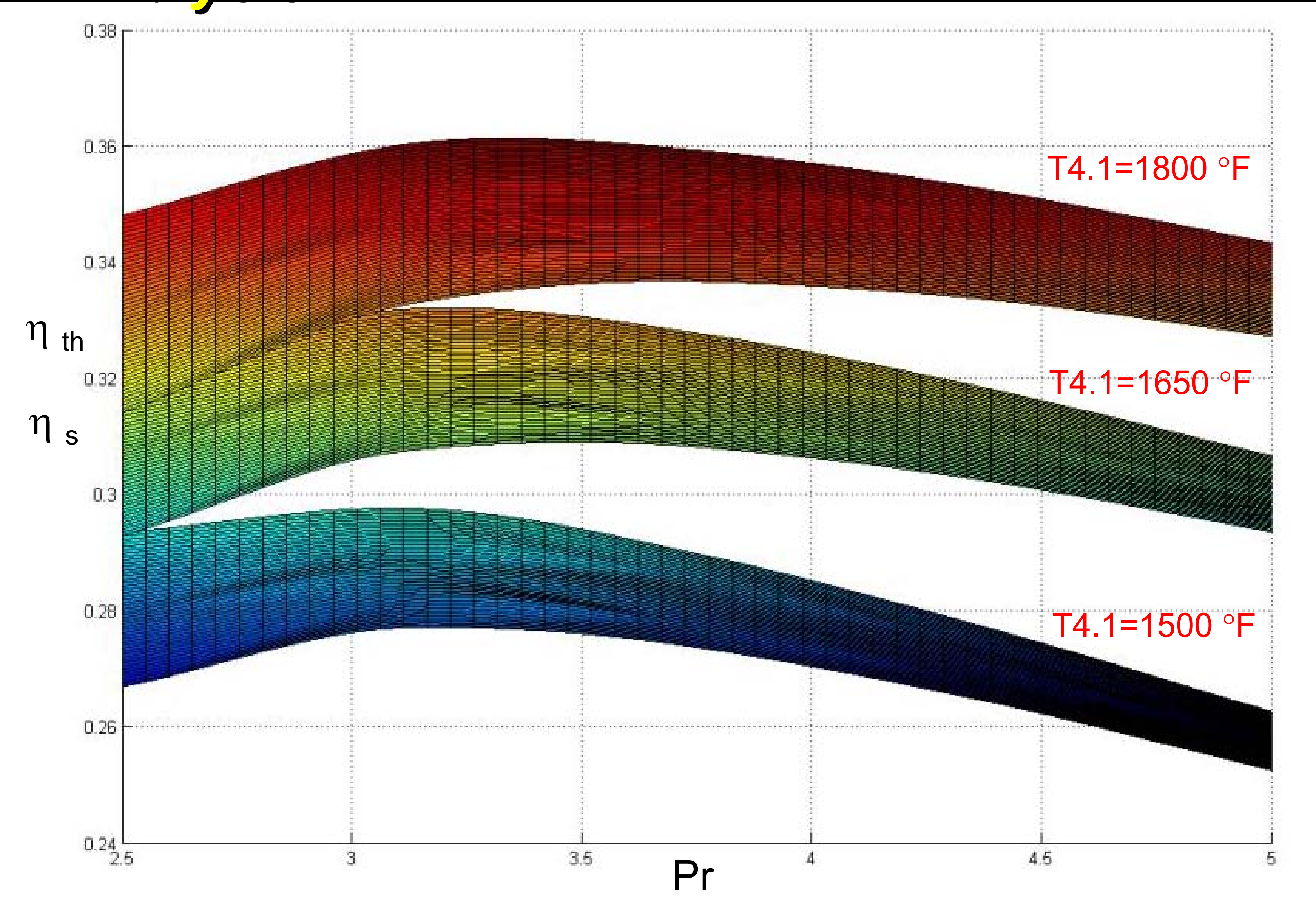
$$W_{tur} = m \cdot (h_{4.1} - h_5)$$

$$i_{tur} = T_o \cdot \left(\Phi_5 - \Phi_{4.1} - R \cdot \ln\left(\frac{P_5}{P_{4.1}} \right) \right) = T_o \cdot (s_5 - s_{4.1})$$

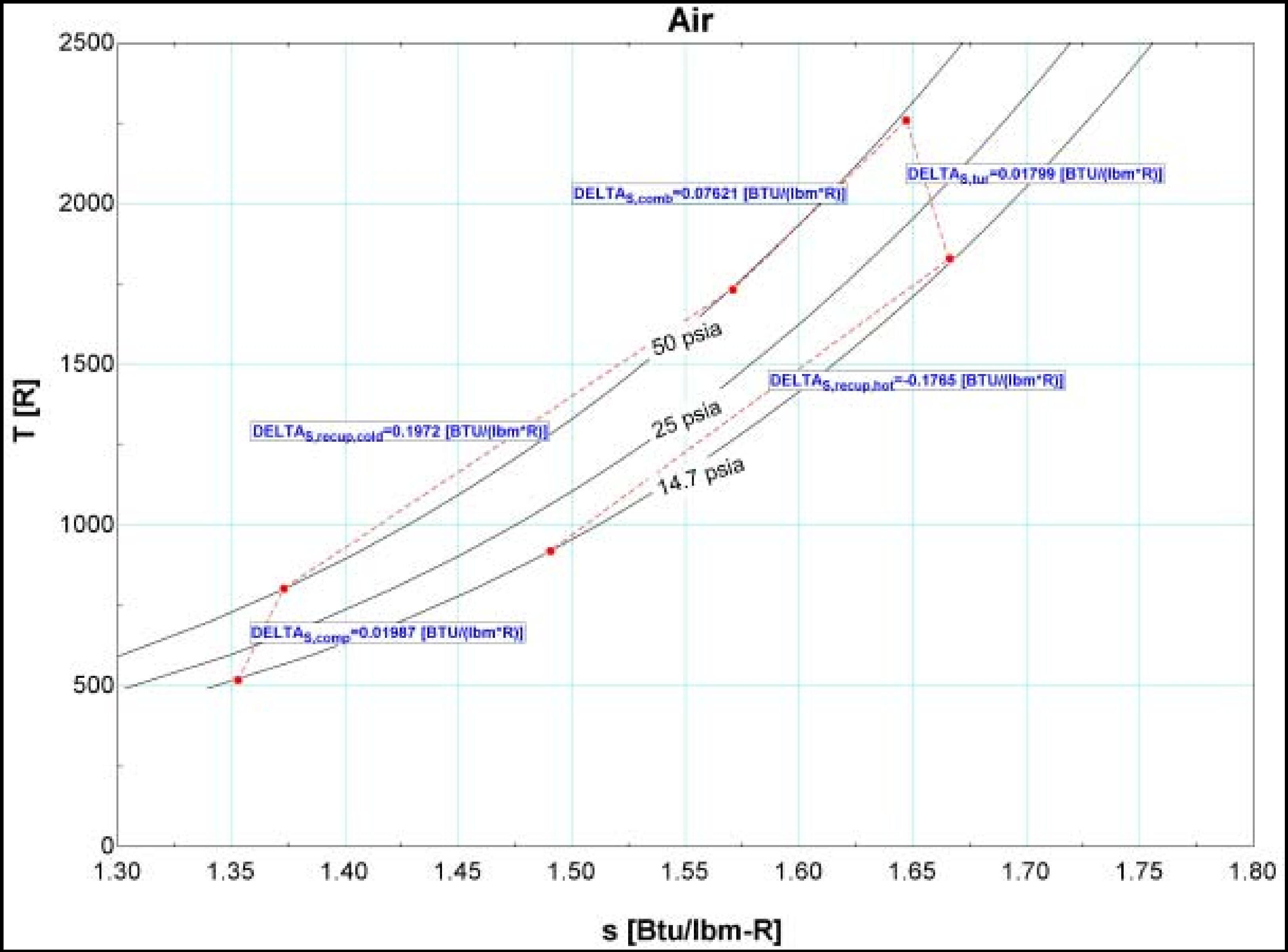
Agreement Between First and Second Law Analysis



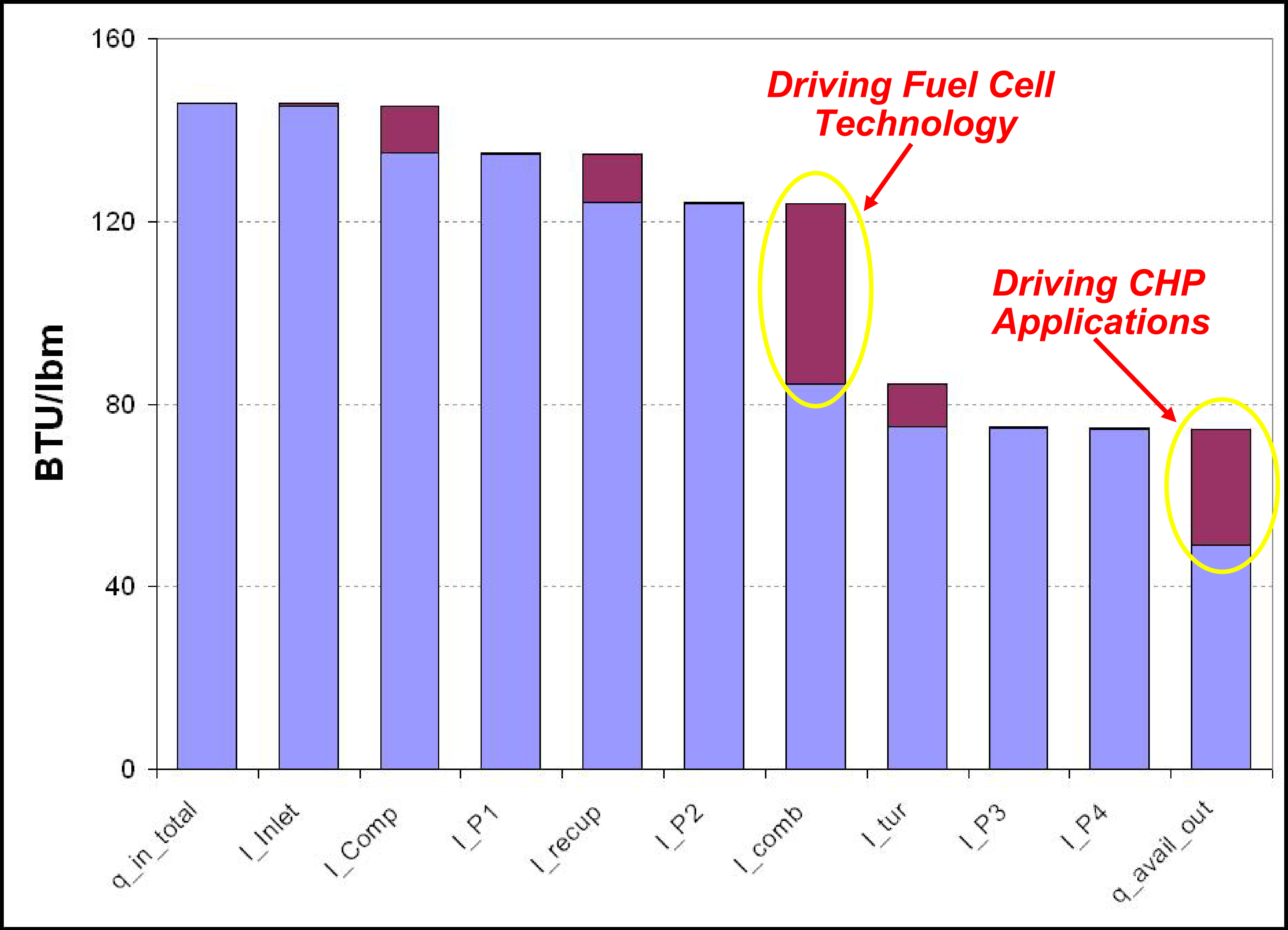
Agreement Between First and Second Law Analysis



Ideal Gas (Air) T-s Diagram



Availability Stack-up



Calculating Combustion Losses

$CH_4 + 3\,(O_2+3.76N_2) = 0.9996\,CO_2 + 0.00036\,CO + 2\,H_2O + 11.26\,N_2 + 0.983\,O_2 + 0.03442\,NO$

$$\sum\left[N_p\cdot\left(h_{fp}{}^{o} + h_p{}^{o}\right)\right] = \sum\left[N_r\cdot\left(h_{fr}{}^{o} + h_r{}^{o}\right)\right] = \left(N\cdot h_f{}^{o}\right)_{CH4}$$

$$\Phi = 0.6667 \qquad T_{prod} = 1784K$$

$$\Delta S_{surr} = 0$$

$$S_{gen} = \Delta S_{sys} = S_{prod} - S_{react} = \sum N_p\cdot S_p - \sum N_r\cdot S_r$$

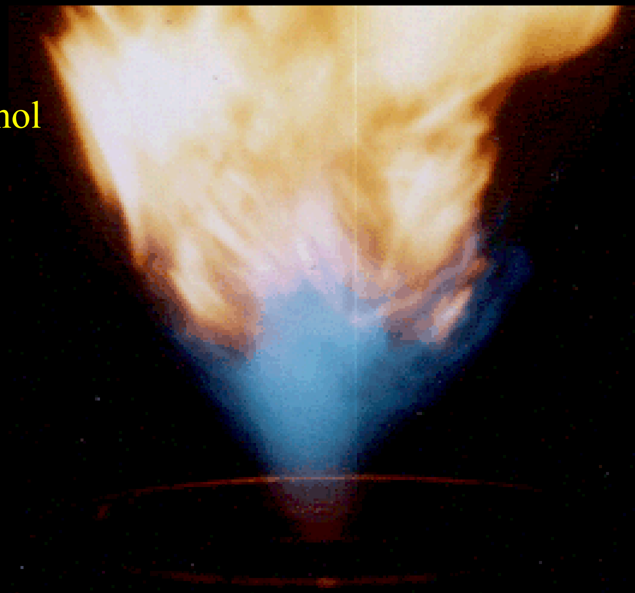
$$S_x = N_x\cdot s_x(T,P_x) = N_x\cdot\left[s_x{}^{o}(T,P_o) - R\cdot\ln\left(y_x\cdot P_{total}\right)\right]$$

$$I = T_o\cdot S_{gen}$$

$$I = 288350\,\frac{kJ}{kmol\cdot K}$$

Calculating Combustion Losses

CH4 + 3 (O2+3.76N2) = 0.9996 C02 + 0.00036 CO + 2 H2O + 11.26 N2 + 0.983 O2 + 0.03442 NO



$$\frac{P_{sat}}{P_{ref}} \cdot \left(4.76 \cdot N_{O2} + N_v\right) = N_v \qquad N_v = 0.463 \cdot \text{kmol} \qquad N_l = 1.537 \cdot \text{kmol}$$

$$Q = \sum \left[N_p \cdot \left(h_{fp}{}^{o} + h_p{}^{o}\right)\right] - \sum \left[N_r \cdot \left(h_{fr}{}^{o} + h_r{}^{o}\right)\right] \qquad T_{prod} = T_o$$

$$Q = -866686 \frac{\text{kJ}}{\text{kmol}}$$

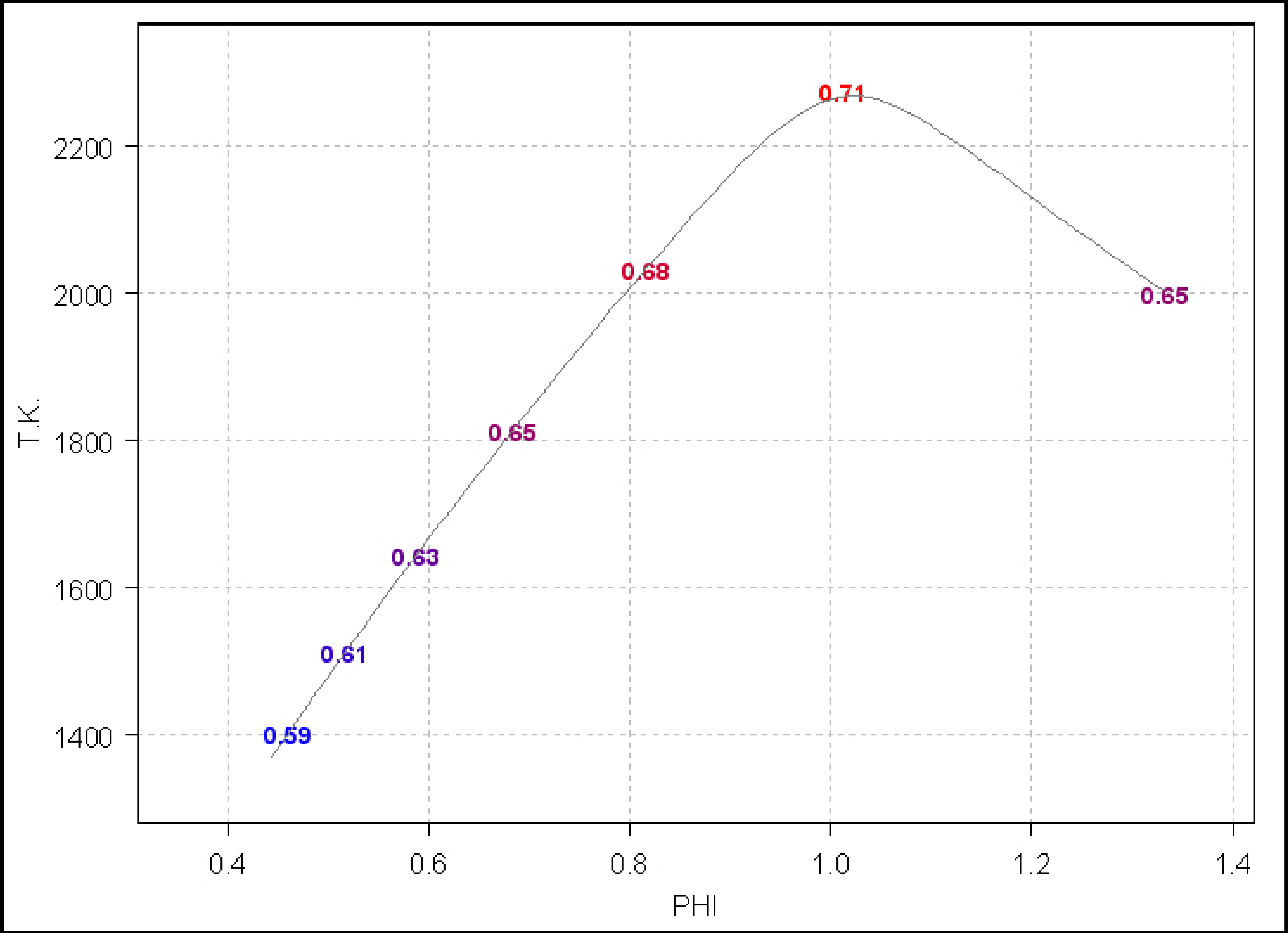
$$\Delta S_{sys} = S_{prod} - S_{react} \qquad S = \sum N_x \cdot \left[s_x{}^{o}\left(T_o, P_o\right) - R \cdot \ln\left(y_x \cdot P_{total}\right)\right]$$

$$\Delta S_{surr} = \frac{-Q_{surr}}{T_o} \qquad S_{gen} = \Delta S_{sys} + \Delta S_{surr} = 2769 \cdot \frac{\text{kJ}}{\text{kmol}_{CH4}}$$

$$I = T_o \cdot S_{gen} = 825268 \frac{\text{kJ}}{\text{kmol}_{CH4}} \qquad \eta_s = \frac{I - W_{irr}}{I} = \frac{825268 - 288350}{825268} = 0.65$$

* Mixing Losses Neglected

Quantifying Combustion Losses



Second Law Summary

- Determines the Maximum Work Potential of Any Thermal/Fluid System
- Provides Greater Insight To System Losses Than A First Law Analysis Alone
- A Powerful Tool To Optimize Thermal Efficiency
- Is No More Difficult To Understand or Implement Than First Law Analysis